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(NASA-CR-152457) CONTRACT TO DESIGN, FABRICATE AND TEST AN ELECTRON BOMBARDED SEMICONDUCTOR (EBS) DEVICE Quarterly Progress Report (Watkins-Johnson Co.) 36 p HC A03/MF A01 CSCL 09C G3/33

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Contract to Design, Fabricate and Test An Electron Bombarded Semiconductor (EBS) Device

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I. SUMMARY

The low resistivity diode has been evaluated in an amplifier with exceptionally good results. A CW output power in excess of 10 watts at 2.34 GHz was obtained. Bandwidth was greater than 400 MHz. A target efficiency of 32 percent was achieved at this power level. Further increases in CW output power are expected with other amplifiers using this diode style.

The characteristics of both the low resistivity diode and the double epitaxial style diode are reported. Both met required breakdown voltage and capacitance voltage characteristics. The double epitaxial style diodes are expected to improve target efficiencies. Another run of diodes is planned pending more complete evaluation of the low resistivity style diode and some impedance evaluation of the radial resonator.

Two more CRT beam testers were completed and the electron beams evaluated. A new reduced size sheet beam gun was completed and its beam characteristics measured with the CRT tester. A pencil beam gun was also evaluated. Both guns will be utilized in future amplifiers.

Some new die attach problems became apparent which considerably hampered progress this quarter. Diodes were cracking after they were brazed with a Au-Ge eutectic to the copper heatsink. After considerable effort the cause of the fracturing was discovered. Incomplete brazing of the die apparently causes highly localized shear areas which eventually,usually within a few days, cause the die to shear. This was observed in many cases, however, some question as to the complete solution still exists. Currently satisfactory die attach has been possible by implementing cleaning immediately before die attach and the use of a new target heating fixture.

Several microstrip fixtures have been built to test and evaluate the impedance and losses of the microstrip resonator design. Results have been fairly consistent with expectations. It appears that a target with better than 56 percent efficiency can be built with the current design.

Some measurements on the coupling capacitor for the radial resonator were made. These measurements established what the maximum diameter coupling capacitor was for the maximum coupling.

Additional milestones were added to the milestone plan as a result of increased funding for the life testing. Several more single diode radial resonator amplifiers will be built and tested in order to reach the 17 watt milestone. Several amplifiers will be built for the life test. Additional impedance evaluation of the radial resonator will be undertaken which is expected to result in higher target efficiencies. An additional diode run is expected once results from the 4.5 ohm-cm evaluation and the radial resonator impedance evaluation are completed.

II. AMPLIFIER RESULTS

Amplifier S/N 9

The target assembly from amplifier S/N 8 was removed intact from the deflection structure and electron gun and remounted on a new tube assembly. This assembly utilized a 3-anode pencil beam gun with an 0.050 inch diameter cathode. The deflection structure utilized an 0.070 inch spaced meander line.

The small diameter pencil beam requires much less cathode current than the large sheet beam guns previously used. However, it was not known at the outset of this test whether sufficient current density was available from the pencil beam gun to achieve the output power levels previously achieved with sheet beam guns. This amplifier was built to see if results, with a single target, could be duplicated on two different guns.

The completed amplifier was operated at 1 percent duty cycle at turn-on. A maximum output power of 20 watts was obtained. This was essentially the same as achieved for S/N 8. Beam current at the 20 watt level was 5 mA as opposed to 20 mA for S/N 8. The beam voltage was 18 kV somewhat lower than the 18.5 kV required for S/N 8. Diode voltage and current were essentially unchanged at -40 volts and 1.4 to 1.5 A peak.

No CW data was obtained for this amplifier. During turn-off the diode current was inadvertently increased by an electron beam transient damaging the diode. This prevented full evaluation of the amplifier for CW operation. Unfortunately another test to determine any CW operation problems will be required. Certainly, however, the 3-anode pencil beam gun will provide adequate beam current density at the diode. This would remain true at higher duty cycles including CW operation. Whether or not there would be gassing problems with the narrow spaced deflection structure can only be determined with another test.

Amplifier S/N 11

This amplifier utilized a glass beam sheet beam gun which was evaluated with a CRT tester, the results of which are reported elsewhere in this report. This was the first amplifier to utilize a diode from the 4.5 ohm-cm run 2082-A2B. Previous amplifiers all utilized diodes with a resistivity of 7 ohm-cm. Both designs utilized the same 5 to 5.5 μm epitaxial thickness. Fabrication and constructional details of both diode types were otherwise identical.

The target assembly construction was far from ideal. Difficulty was experienced in obtaining all of the wirebonds desired due to a slightly higher spacing between the resonator surface and the diode surface. This resulted from too much plating on the resonator support pillars. Normally 26 - 1 1/2 mil diameter aluminum wire bonds are utilized in connecting the radial resonator to the diode (Fig. 1). In this case only 16 of the 26 wirebonds were achieved. This reduced the resonant frequency to 2.34 GHz rather than the desired 2.6 GHz.

The BV characteristics of this diode are somewhat different than the previous run (Fig. 2). Due to the lower resistivity a somewhat lower BV is expected - 90 to 95 V. This, however, is entirely adequate for the operating voltage, 30 - 35 volts required. This diode had been under CW beam illumination for more than 100 hours with the diode terminals short circuited with no degradation in BV or increase in leakage current.

Initially the amplifier was operated on a 1 percent duty cycle with an on-time of 50 μsec. The beam parameters were typical of previous amplifiers. Due to the smaller size cathode with a new geometrical design a considerable reduction of heater power was observed (24 watts to 12.3 watts). This is a measure of what should be possible with an improved cathode heater design. At the 1 percent duty cycle somewhat dissapointing peak output powers were observed. Under best conditions only 17.7 watts was obtained. This required a beam current of near 8 mA at a target voltage of 40 volts and peak current of 1.3 amperes.

Increasing the duty cycle from 1 to 25 percent very little change, if any, in peak output power was observed (Fig. 3). This was some improvement over previous amplifiers but not an apparently significant one at this point in the testing. It certainly was an indication that good CW results should be expected which was again not any different than previous amplifiers. Target efficiency remained in the 36 to 38 percent region for these duty cycles.

The most phenomenal results were obtained from CW operation (Fig. 4). A maximum output power of 10 watts was observed during this test. The corresponding target current and voltage was 1.1 amperes and 30 volts. A target efficiency of 32 percent was observed. The frequency of operation for these results was 2.34 GHz (Fig. 5). A bandwidth (-3 dB) of over 400 MHz was achieved which was well in excess of the 180 to 190 MHz achieved with previous amplifiers.

Performance of this amplifier was marred by a misadjustment of the tuning capacitor. The force of the capacitor against the resonator caused the wirebonds from the diode to the resonator to break. Eventually this resulted in the operating frequency to decrease below 2 GHz with low output power.

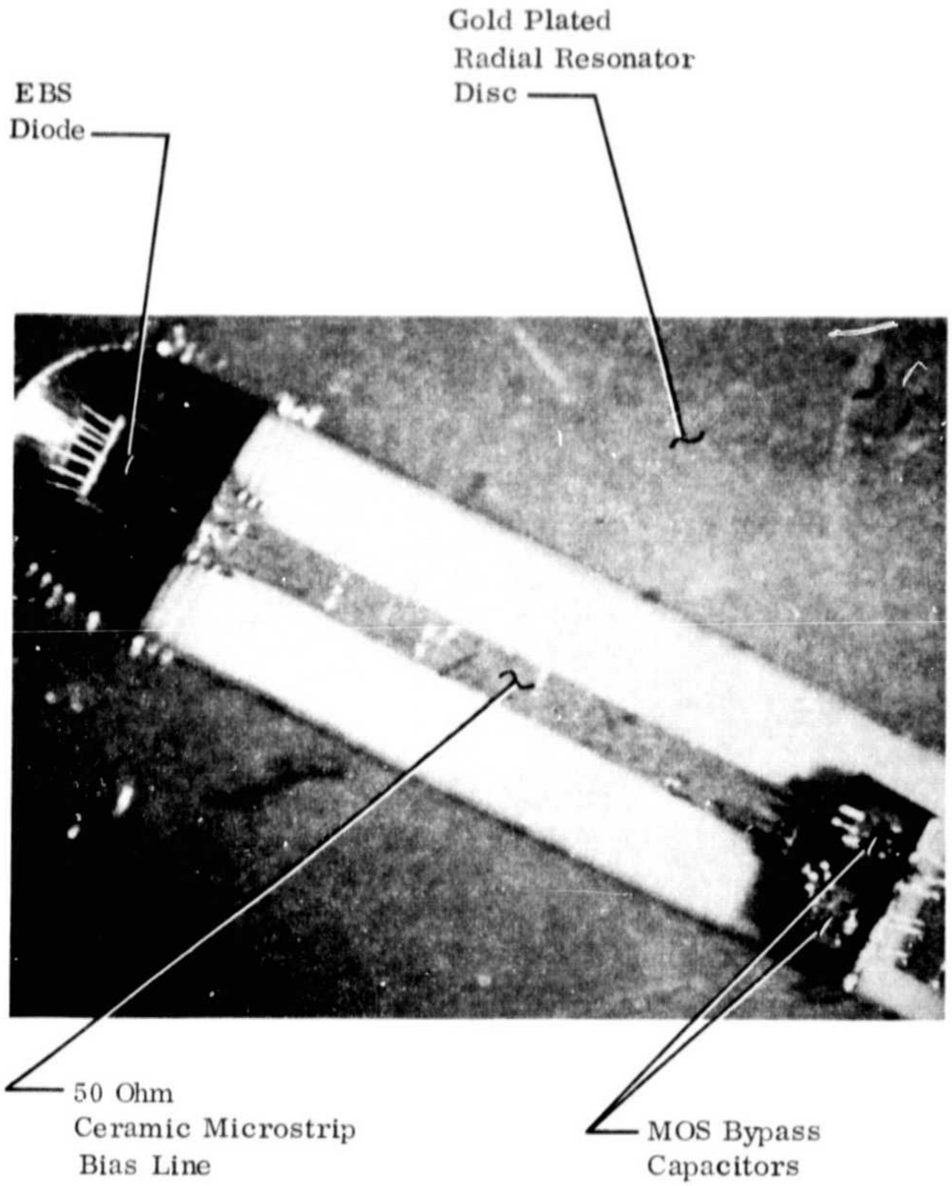

Figure 1 - Expanded view of the target from S/N 11

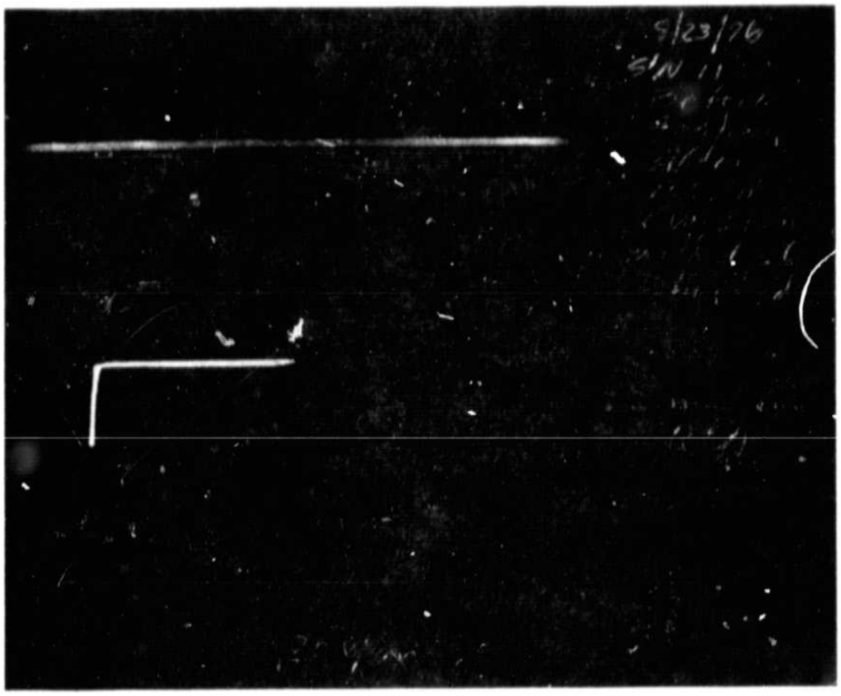

Figure 2 - Diode BV characteristics after over 100 hours of CW electron beam illumination S/N 11.

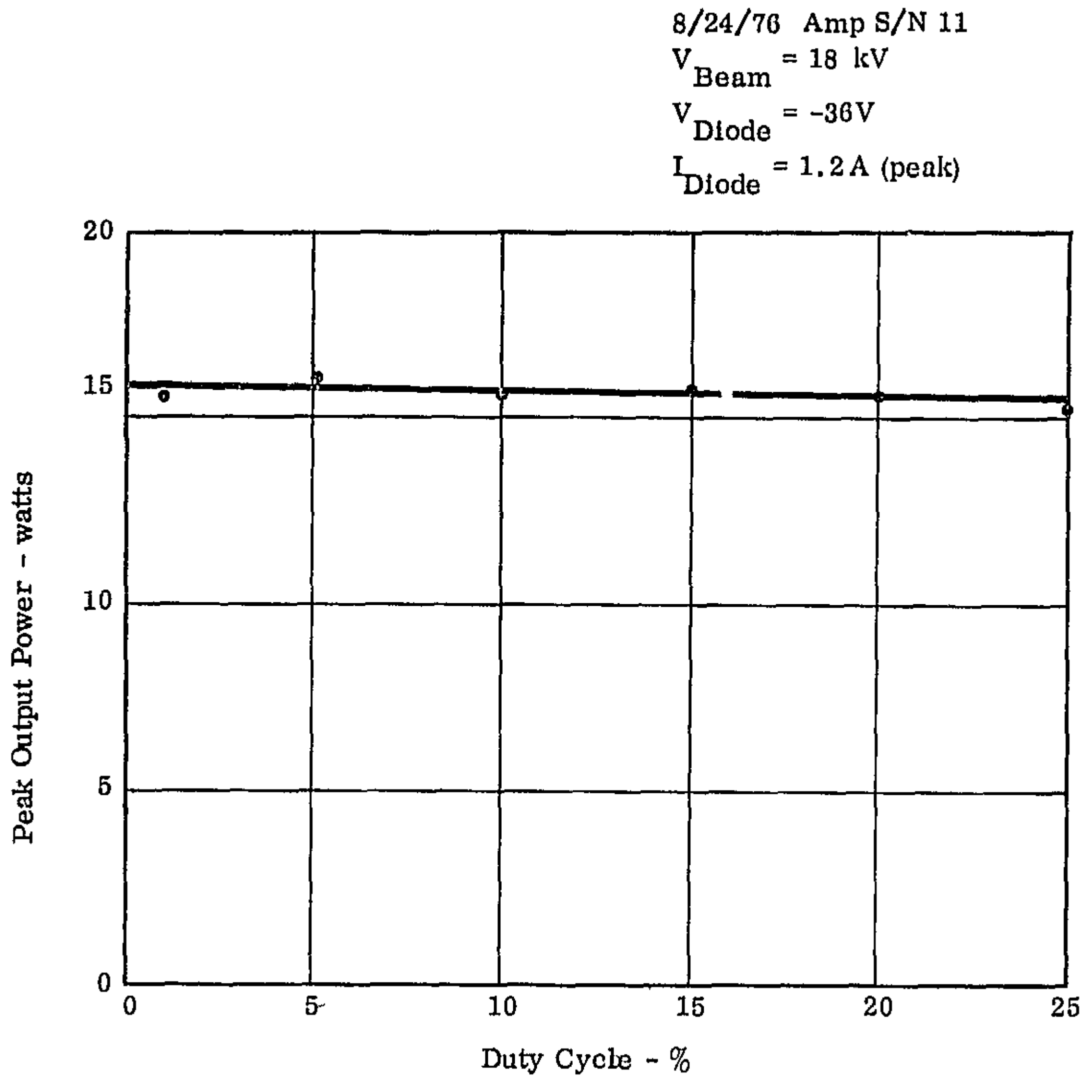

Figure 3 - Peak output power versus duty cycle for amplifier S/N 11.

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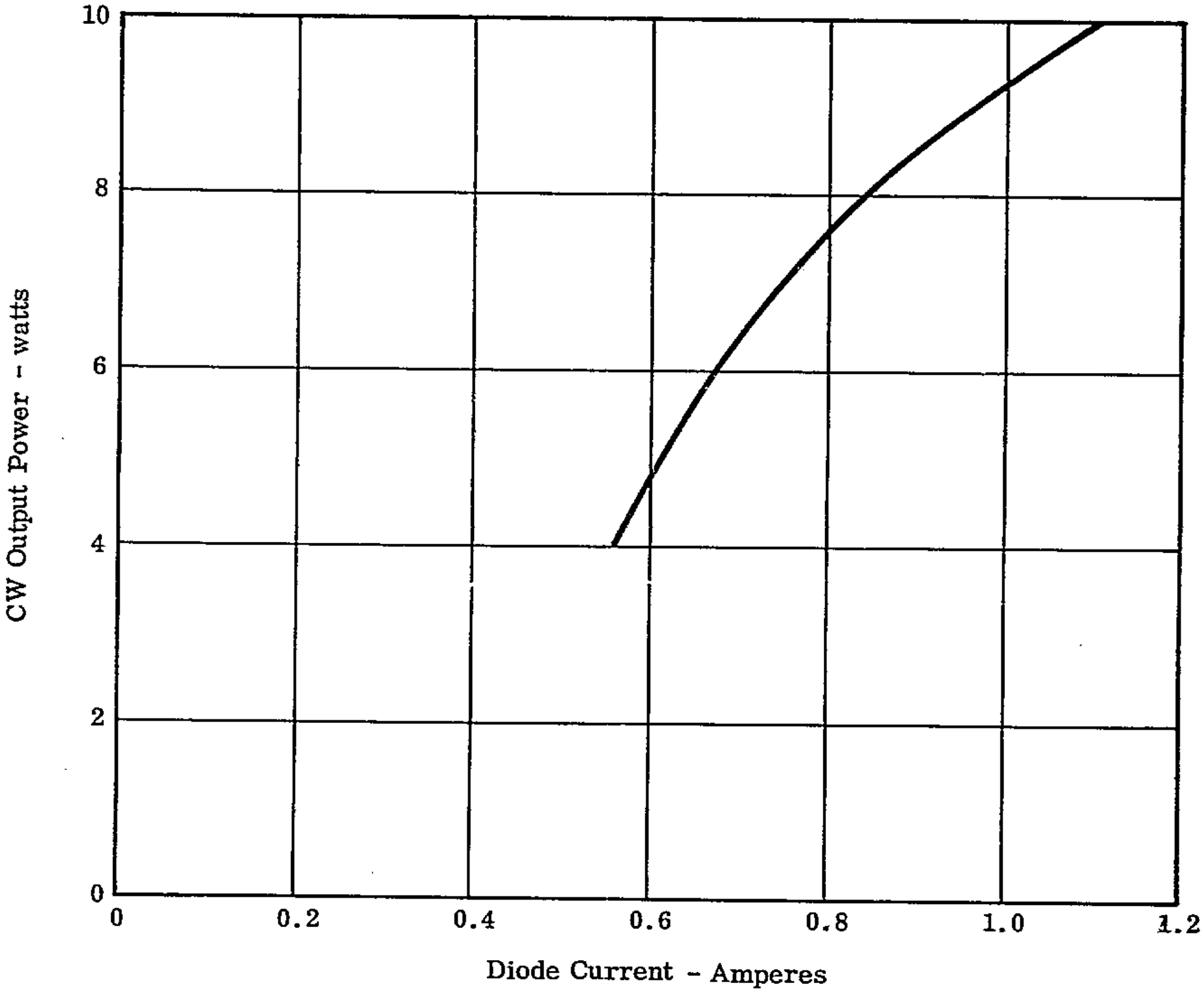

Figure 4 - CW Output power versus diode current S/N 11.

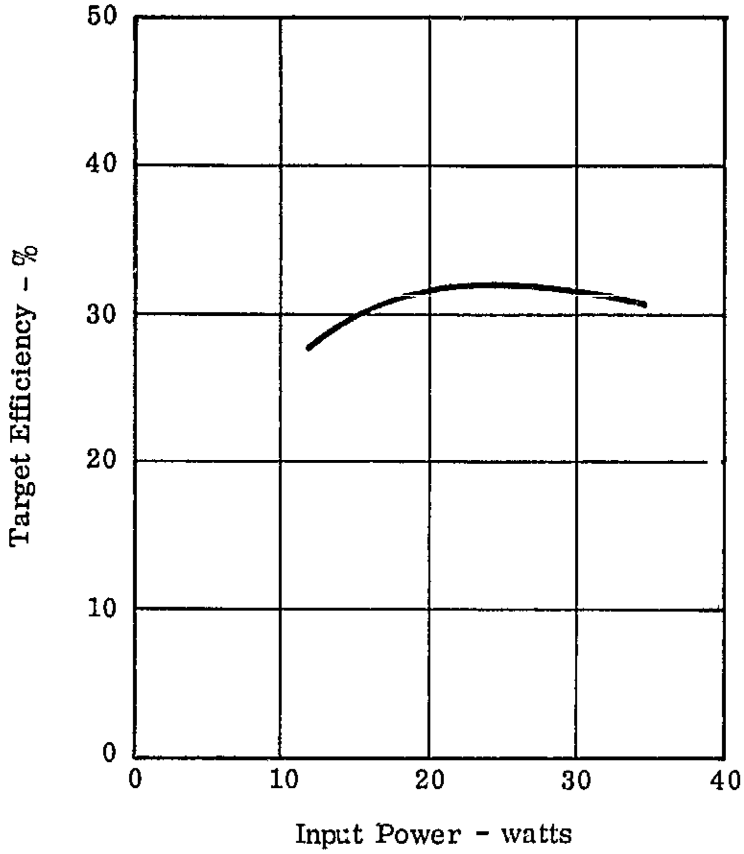

Figure 5 - Target efficiency versus input power S/N 11.

The improved output power achieved by this amplifier is a result of the reduced resistivity diode. This permits a lower operating impedance at the diode. Previous diodes could not operate at a sufficiently low impedance without having the diode current run away. In addition improvements in die attach may have reduced the operating temperature of the diode preventing hot spots which could result in current run away. Since the amplifier was destroyed before the full potential of the amplifier was exhausted it is expected that higher power levels will be achieved in future amplifiers.

III. DIODE FABRICATION

The standard EBS diode is fabricated from a silicon wafer having an n epitaxial region deposited ona n^+ substrate. A heavily doped region (p^+) using boron is formed on the epi material forming a junction of 0.4 μm depth. For low frequency amplifiers this form of construction works well.

For higher frequency devices improved diode efficiency may result by forming the junction at a significant depth into the epitaxial region. For the particular amplifier in question a depth of 2 μm for a 6 μm thick diode has been shown by calculation to be significantly more efficient than a shallow junction.

The double epi diodes were fabricated from wafers with a double epitaxial deposition. First an n^+ silicon waver (.005 - .02 ohm-cm) was deposited with a 6.0 μm thick phosphorus doped 7 ohm-cm epitaxial material. Following this deposition a p-type boron doped epitaxial layer of 2.9 μm thickness was deposited. During processing of the diode a p^+ boron doped region of 0.4 μm depth was formed on the p-type material preventing depletion of the diode surface during operation. The resulting doping profile is shown in Fig. 6.

These diodes have been completed to the backside grinding and subsequent metallization. The BV ranges from 75 to 90 volts which is within the region expected (Fig. 7). The CV plot for this diode appears in Fig. 8.

The low resistivity diode run, 2082-A2B with a 4.5 ohm-cm epitaxial region BV characteristics are shown in Fig. 9. Breakdown voltages ranged from 80 volts to 95 volts with leakage currents below 0.1 μA. The CV plot for this run is shown in Fig. 10. The depletion voltage of 25 volts yields a diode thickness of 5.7 μm for the 4.5 ohm-cm material. These numbers compare well with measurements made on the material.

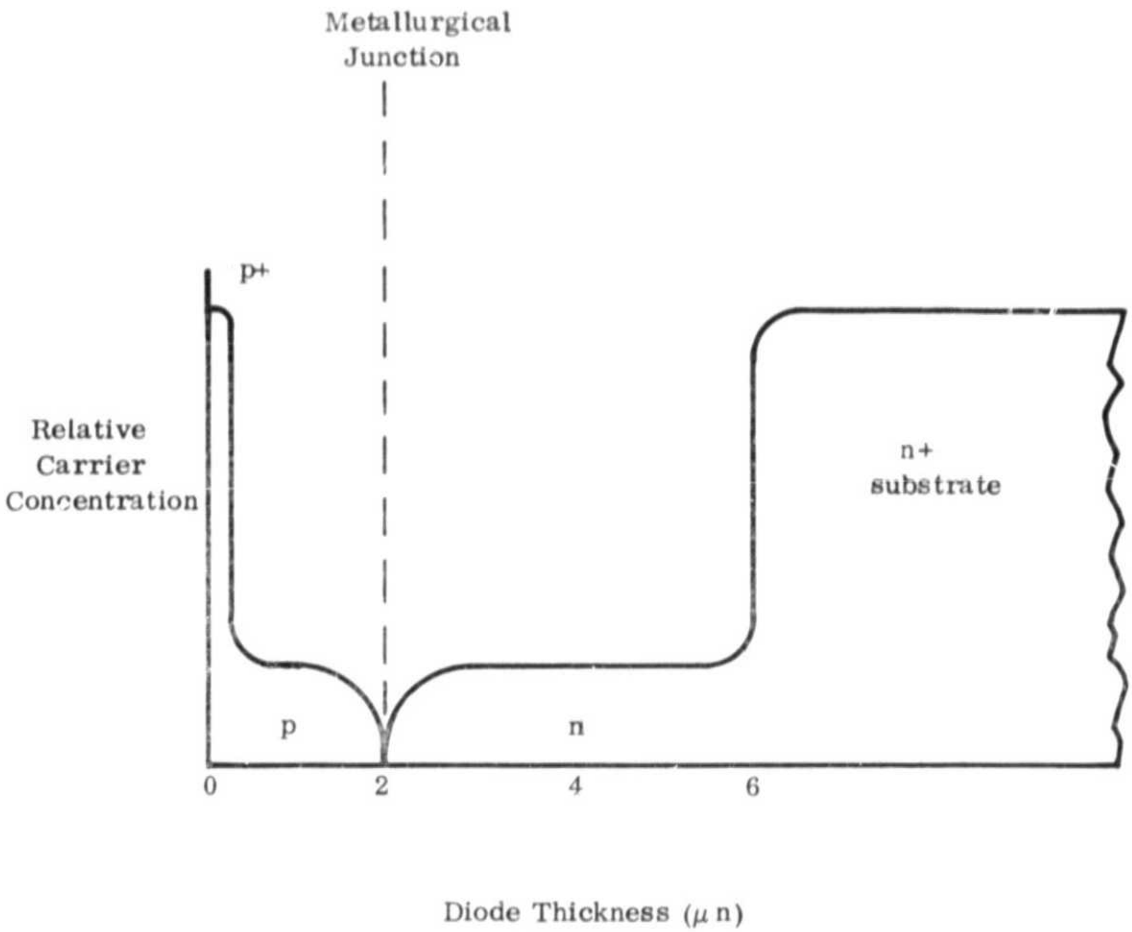

Figure 6 - Double epitaxial EBS diode doping profile.

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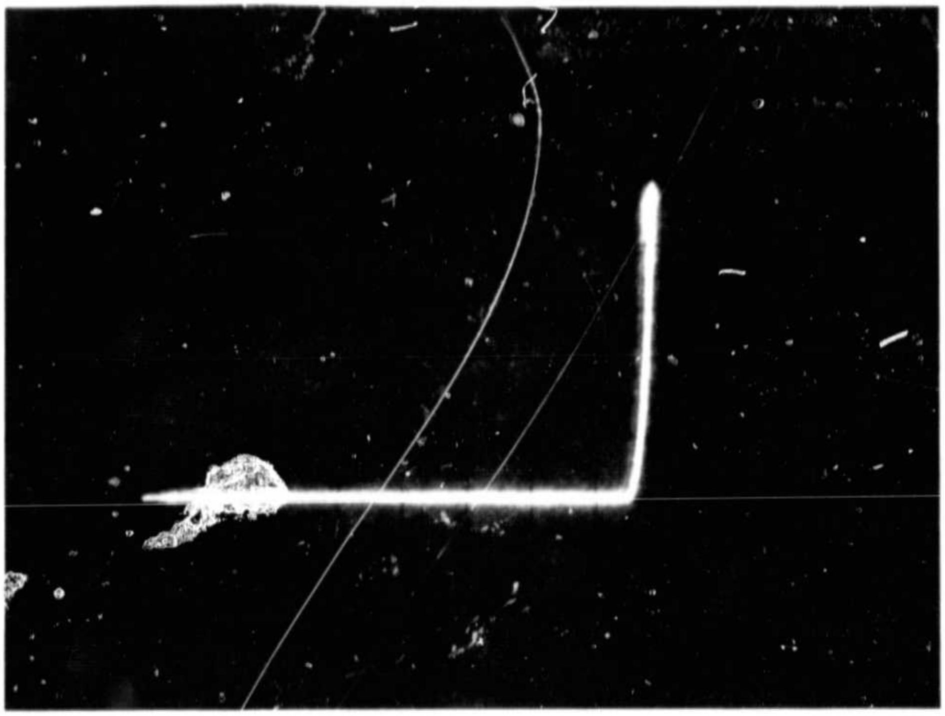

Vertical Scale 0.1 μA/cm
Horizontal Scale 10 volts/cm

Figure 7 - BV characteristics of run 2082-B1 double epitaxial diode

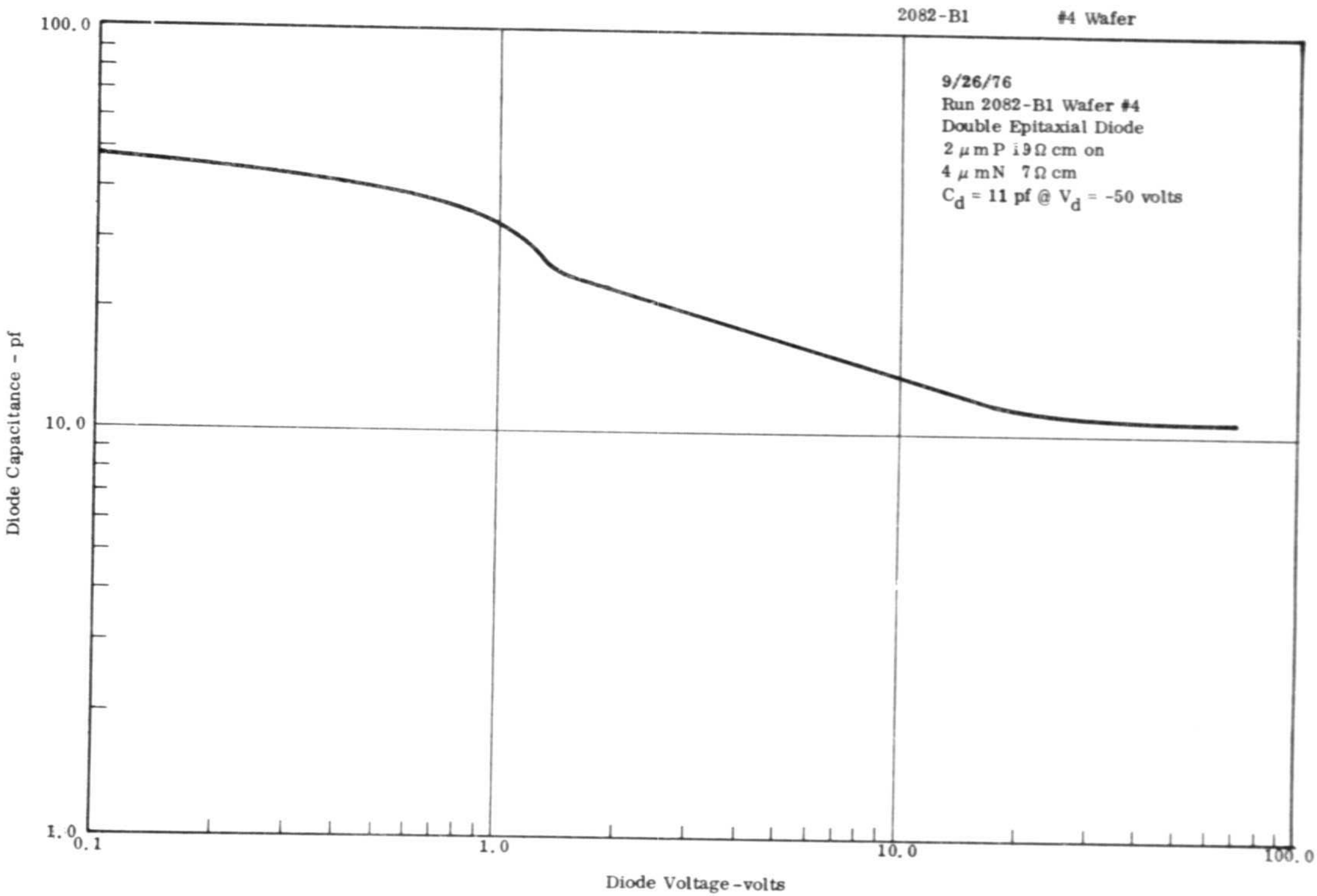

Figure 8 - CV plot of run 2082-B1 Wafer No. 4

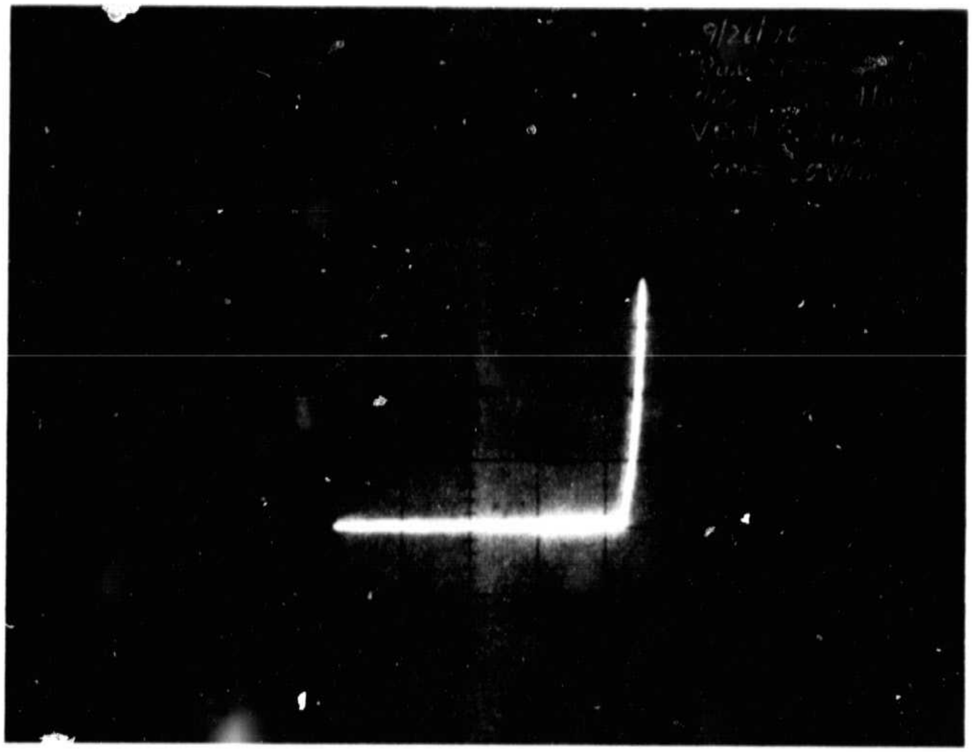

Figure 9 - BV characteristics of run 2082-A2B 4.5Ω · cm aluminum diode

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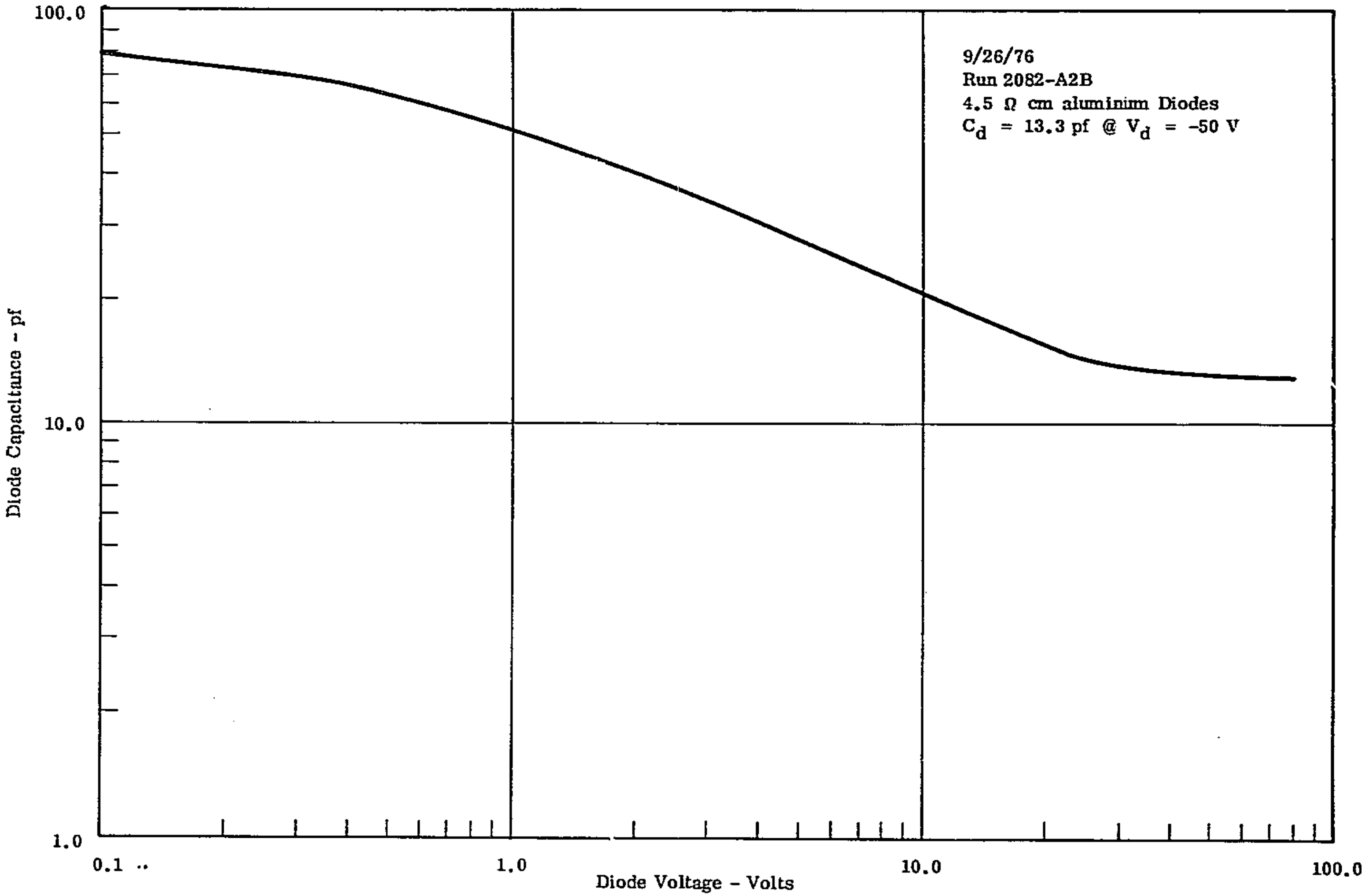


Figure 10 - CV plot for run 2082-A2B

IV. ELECTRON BEAM EVALUATION

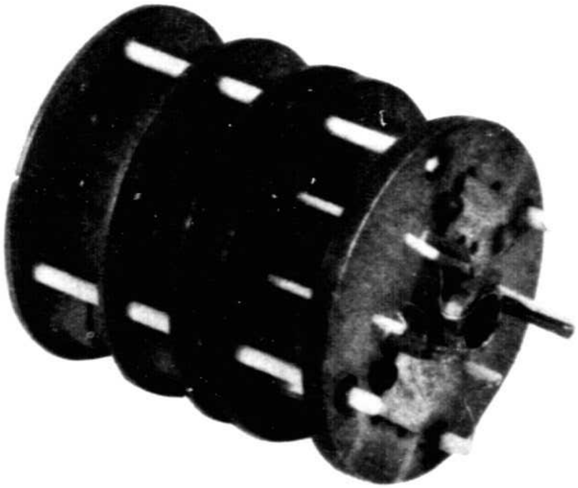
Two different electron guns were evaluated during this period. The first one evaluated was a sheet beam gun using the glass beaded type of construction. Fig. 11 shows the two types of construction used. The glass beaded construction has the advantage of taking much less time both in machining and assembling the gun. In addition to using the glass beaded construction a new cathode design was utilized which results in significantly reduced heater power (Fig. 12). A heater power of 12.3 watts was required as compared to 24.5 watts for the longer 0.75 inch cathodes used on earlier guns. Further reductions are certainly possible with careful design to reduce conductive and radiative heat losses.

This gun was evaluated immediately prior to using it on amplifier S/N 11 with a CRT display. Accurate measurement of beam width was typically difficult using a phosphor display. In addition, the beam shape was not uniformly rectangular at the screen. However, with a small magnet the beam shape could be modified to give a more desirable shape at the screen.

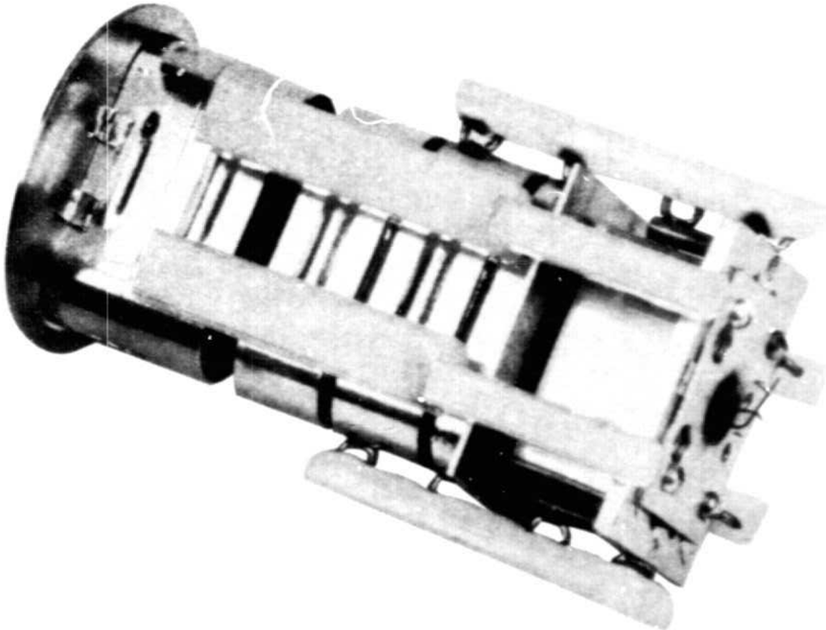
The beam width was measured at a single point, near the center of the display, as a function of the beam current for a set of beam voltages (Fig. 13). As with previous guns the smallest beam is obtained for the highest beam voltage. The beam width varies nearly linearly with beam current. Also observed was an increase in the long dimension of the beam from .3 inch to .5 inch over the beam current range of 2 to 10 mA.

Another electron beam gun was tested using the CRT display. This gun was a 3 anode pencil beam gun with an 0.050 inch diameter cathode. The deflection structure used was an impregnated tungsten type.

The effect of the various beam parameters upon the beam diameter at a distance of approximately 10 inches between the cathode and CRT screen was studied at various beam current levels. The effect of anode 1 voltage (Fig. 14) was to decrease the beam diameter for increasing voltages at the higher beam currents. At the lower current levels the effect was lessened. Anode 2 voltage had a slight effect which was easily optimized for any setting of Anode 1, Anode 3 and beam current. The effect of beam voltage was also to decrease the beam diameter (Fig. 15) for the higher values of beam current with increasing beam voltage. At lower current levels the beam diameter tended to become the same for all beam voltages.



Fitted Ceramic Rod



Glass Beaded

Figure 11 - Types of construction utilized for the sheet beam electron gun structures

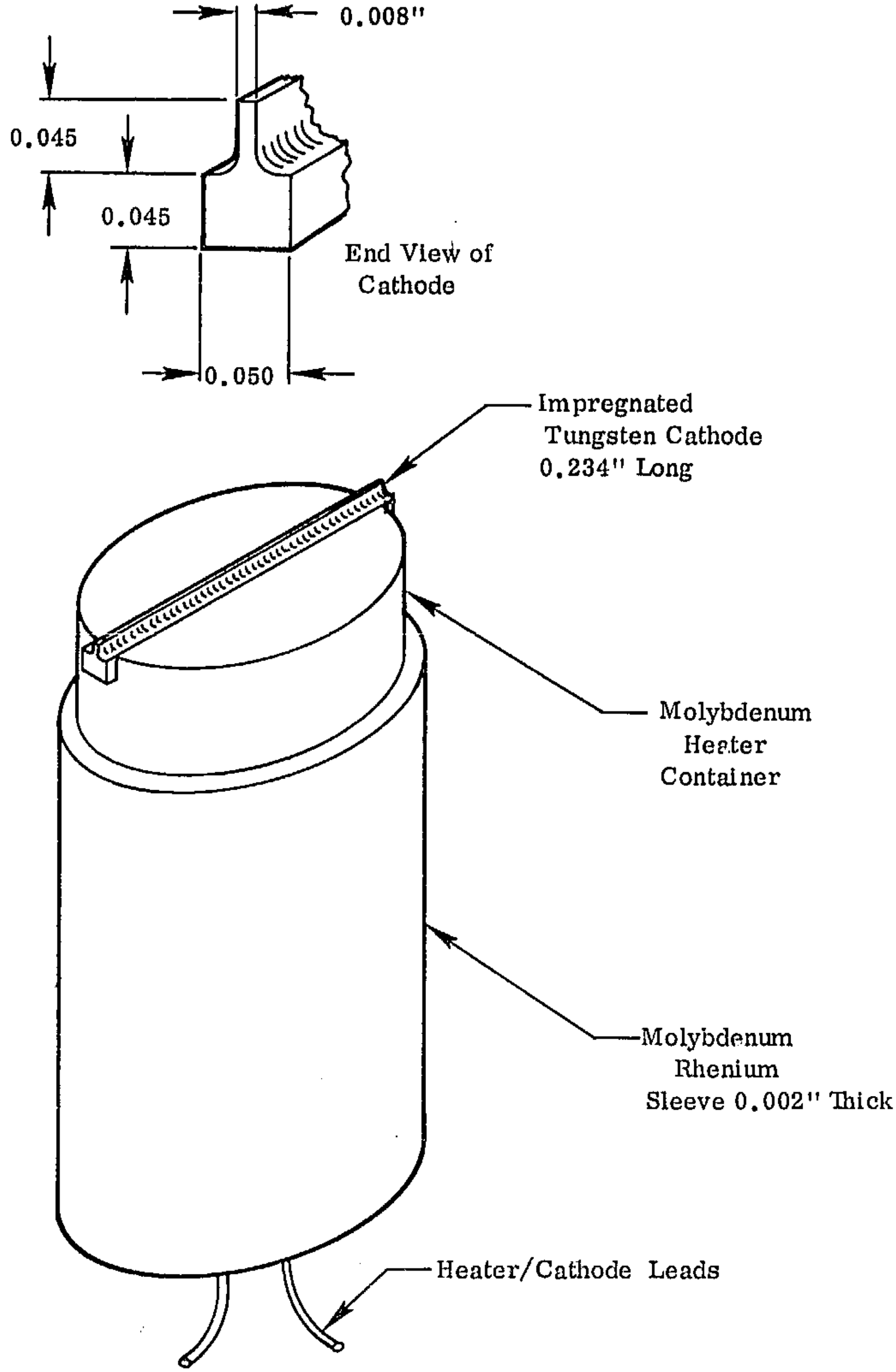


Figure 12. New Form of Cathode Construction

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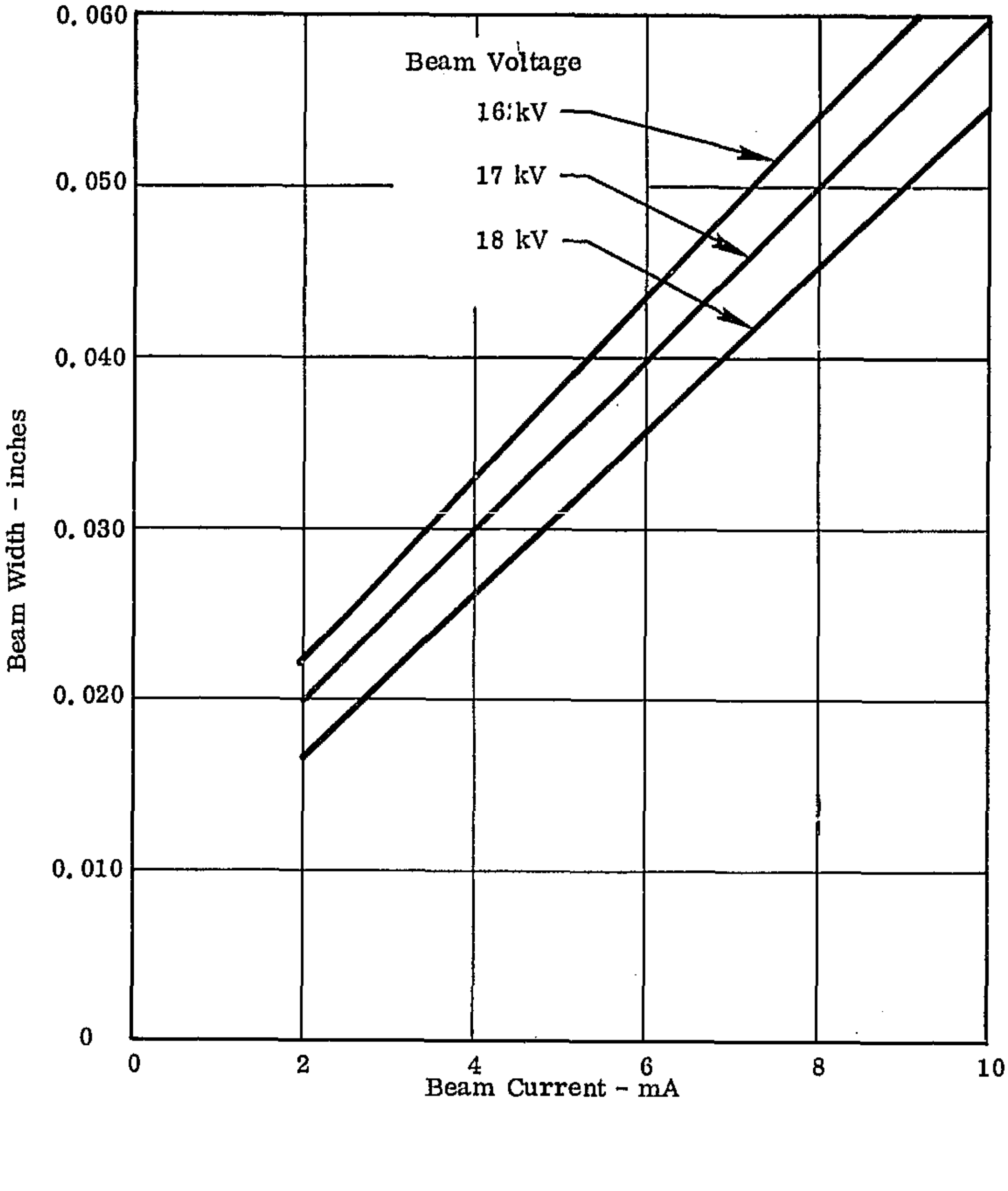

Figure 13 - Beam width versus beam current with beam voltage as a parameter.

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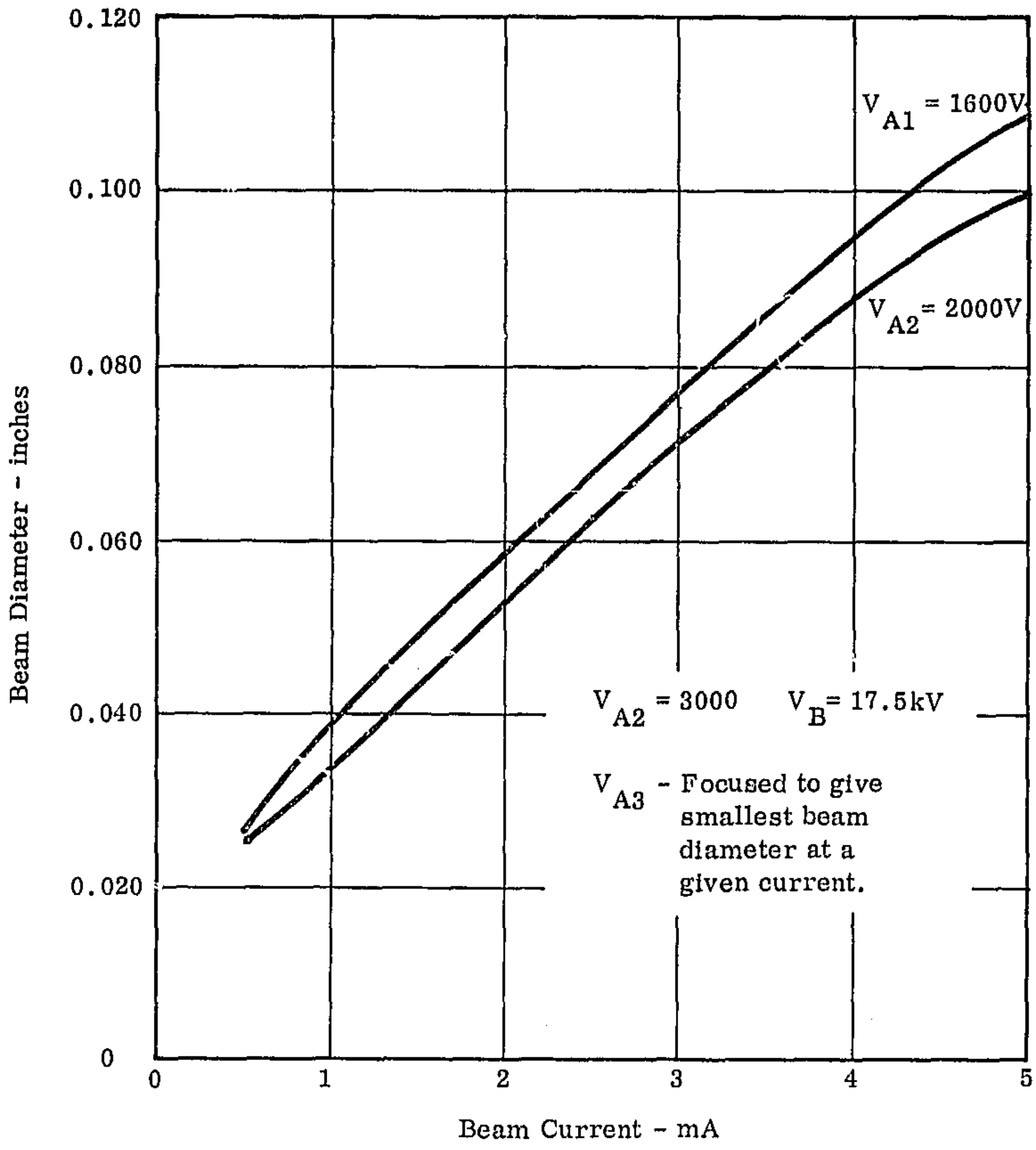

Figure 14 - Effect of anode 1 voltage on focused beam diameter.

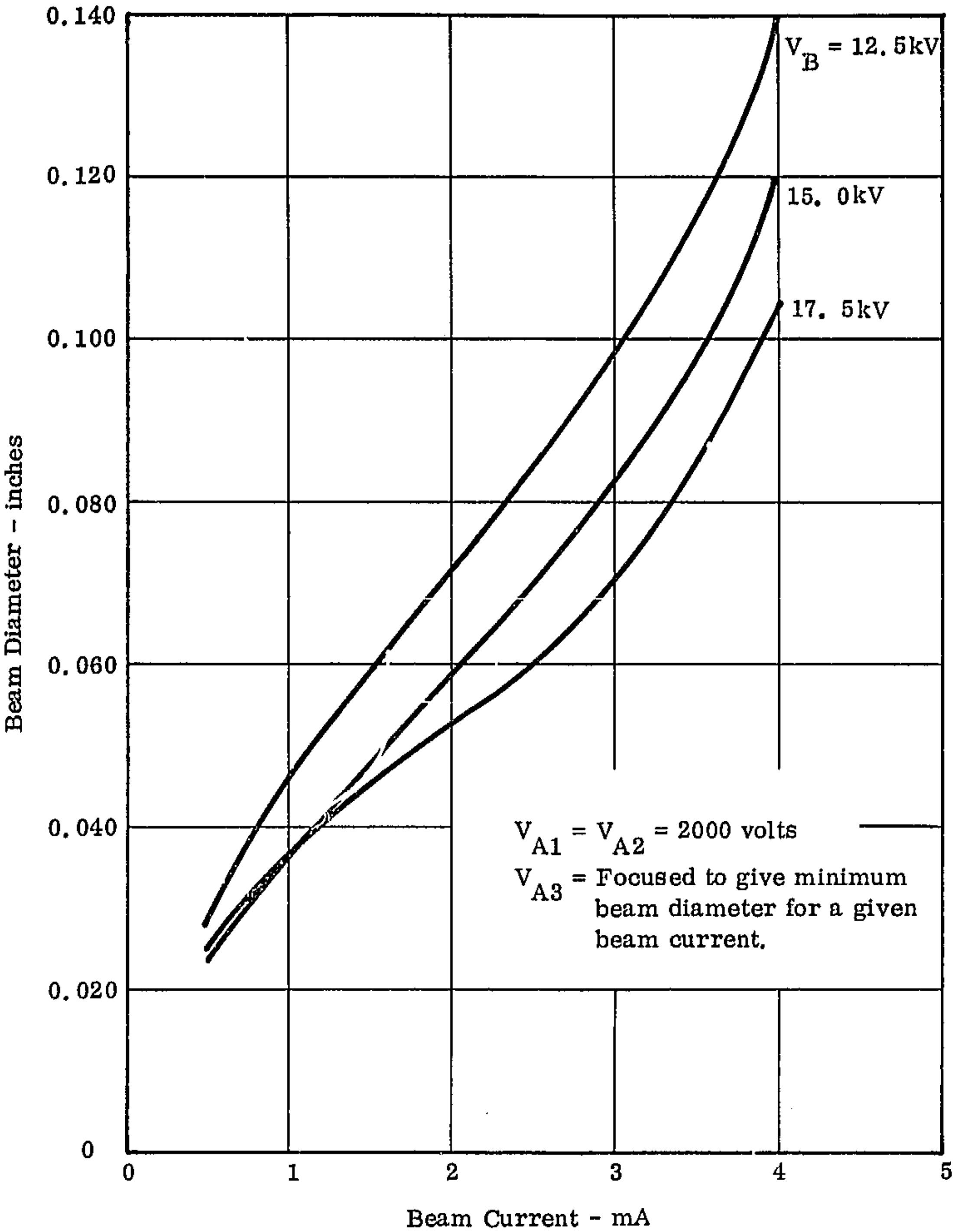

Figure 15 - Effect of beam voltage on focused beam diameter.

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For both type of guns evaluated it was quite clear that more electron gun design work was required. The sheet beam gun still has too large a beam width with poor control on beam width across the beam length. Similarly the pencil beam is much larger in diameter than is required for a single pair diode target. Beam diameter most likely in the 0.020 inch size at the required current levels could be obtained by reducing the cathode size.

V. DIE ATTACH EVALUATION

During the fabrication of a target with diodes from run 2082-A2A several attempts at die attachment of the diode resulted in cracking of the die (Fig. 16). These cracks appeared either immediately after cool-down or up to a day later. Upon examination it appeared as if in all cases very non-uniform die attachment of the die to the preform also existed. Cracks sometimes appear along the area where the die was wet with the gold-germanium braze material. In all cases, the gold-germanium very nicely wet the copper heatsink but poorly wet the platinum metallization on the diode.

This occurrence of diodes cracking during or after die attach was not the first. Previously cracks were observed which were determined to be caused by the fixture used to position and apply pressure to the die during attachment. The cracking observed this time did not seem to be related to the die attach fixture. Instead, initial guesses indicated the cracks were caused by stresses induced from erratic wetting of the diode's back surface. That is, the gold germanium braze material would flow smoothly between the copper heatsink and the backside of the diode but an actual braze would occur for only a small portion of the diode area.

After considerable evaluation, which produced many indeterminate results, it was concluded that cracking of the diode occurred from incomplete wetting of the diode which localized stresses along the silicon braze interface. Cracking would frequently be observed along this interface (Fig. 17). In this case, the area of fracture outlined the only area for which the braze material adhered to the diode.

The incomplete wetting of the diode seems to be caused by several factors. The most significant is in the lack of affinity of the Au-Ge braze material for the platinum backed diode. In all cases observed (probably greater than 100) during these tests the Au-Ge had a strong affinity for the copper,flowing and wetting the surface very nicely. But in no case observed did the same affinity for platinum exist.

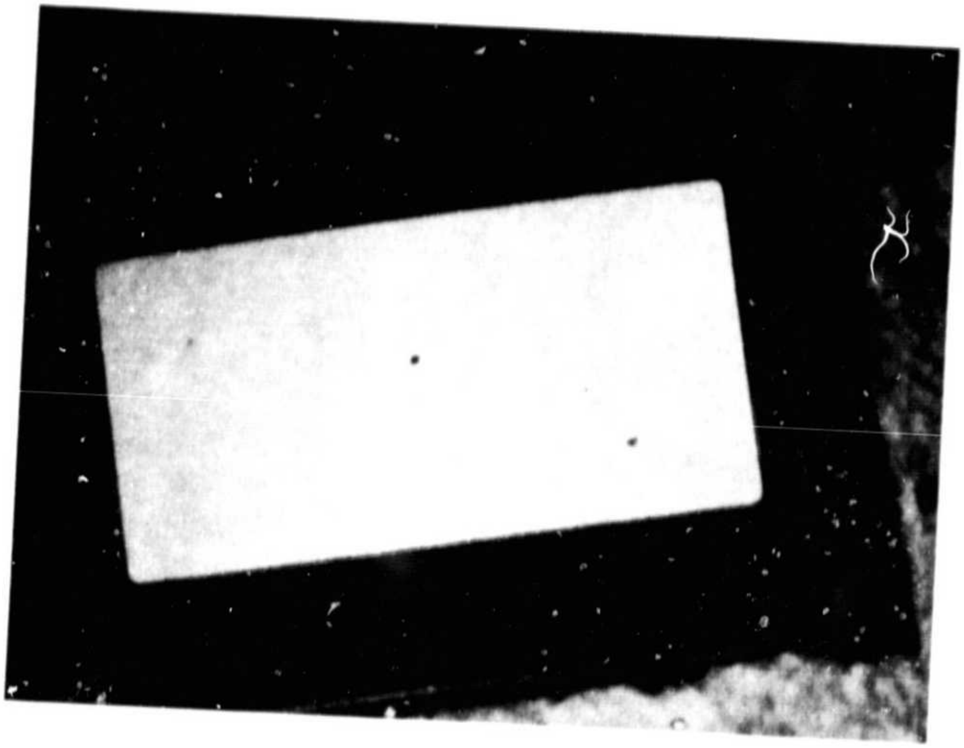

Figure 16 - Diode showing crack in surface after attachment to copper heatsink.

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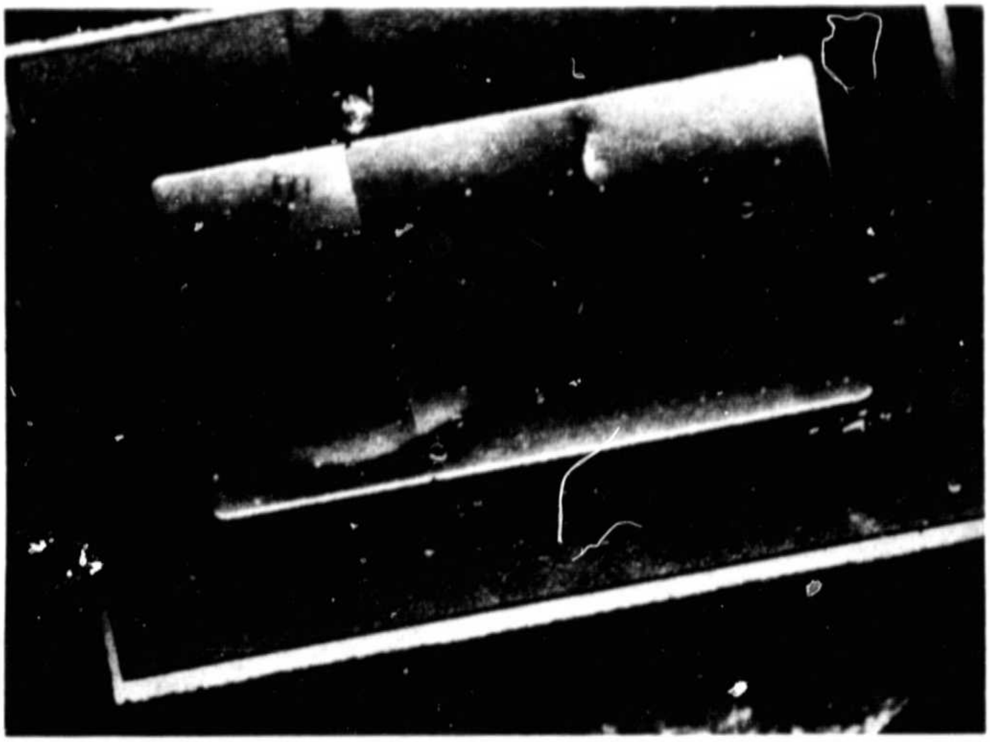

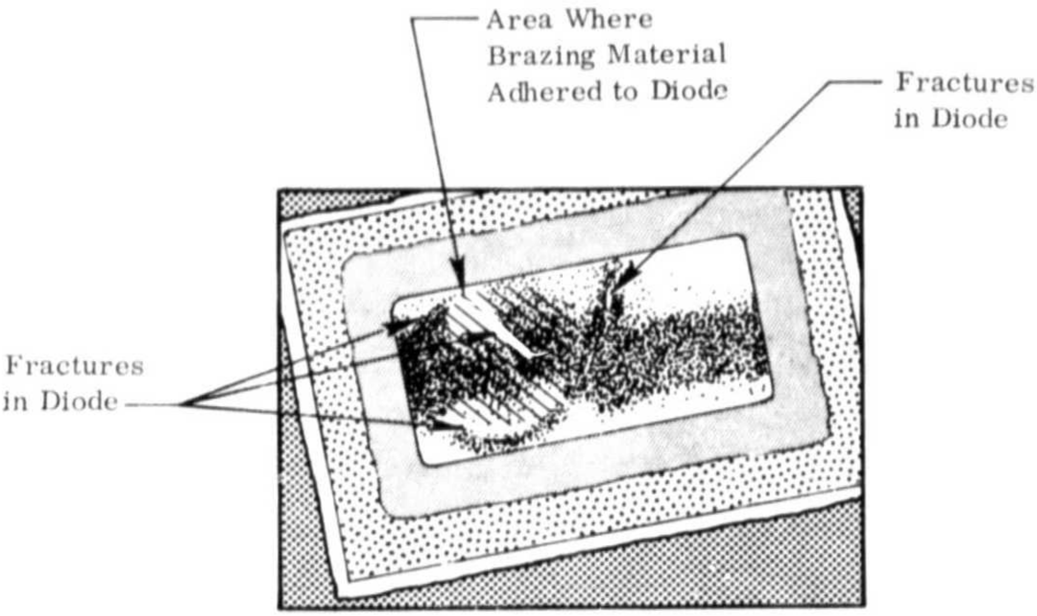

Figure 17 - Diode fractured during die attachment around the brazed area.

Cleaning of the die seemed to be very important. Yet no definitive actions could be taken to insure good adherence with a certain precise cleaning procedure. In fact, the only important thing seemed to be cleaning of both the die and the preform immediately before die attachment. However, this was not always true. The cleaning used was a typical organic solvent sequence with DI water rinse.

The laser scribing of the die probably influenced negatively the wetting of the die on the edges. Since the die is laser scribed entirely through (6 mils of silicon) some of the material ejected from the cut coats the area near the cut. This is protected by an organic material similar to photoresist which is cleaned off after laser scribing of the die. Some of the residue is left on the surface to be die attached, and causes that surface not to wet. However, this area is usually not important to achieving good heatsinking of the active area.

Improvement of the die attach seems to have been obtained by instituting cleaning immediately before die attachment and reducing the thermal mass of the die attach station. This resulted in more rapid increase of temperature at the diode which appears to have been necessary for good die attach.

VI. MICROSTRIP TARGET EVALUATION

The configuration planned for the microstrip target is shown in Fig. 18. Several tasks remain to be completed before this target may be built and tested. Some progress toward completing these tasks has been completed.

The microstrip resonator dimensions have been determined (Fig. 19). Several tests have been made to insure that the desired impedances are provided with the dimensions chosen.

A test fixture was made which permits connection of the resonator to a SMA type connector (Fig. 20). Wirebonds were fixed to the end of the resonator to the RF ground plane and the phase length of the resonator was checked. Using the effective dielectric constants determined from the previous halfwave resonator tests the resonator dimensions appear to be correct. The RF losses were measured and determined to be 0.3 ohm. This loss measurement has an accuracy of within ± 0.2 ohm.

A test target was next fabricated using the same resonator ceramic. The wirebonds to RF ground were replaced with wirebonds to a diode die attached to the fixture (Fig. 21). The diode was biased at a -30 volts and the input impedance at the end of the 50 ohm ceramic microstrip line was measured. An impedance at resonance of 9.53 ohm was measured for Z_{in} at 2.6 GHz. This is ideal providing that losses are sufficiently low.

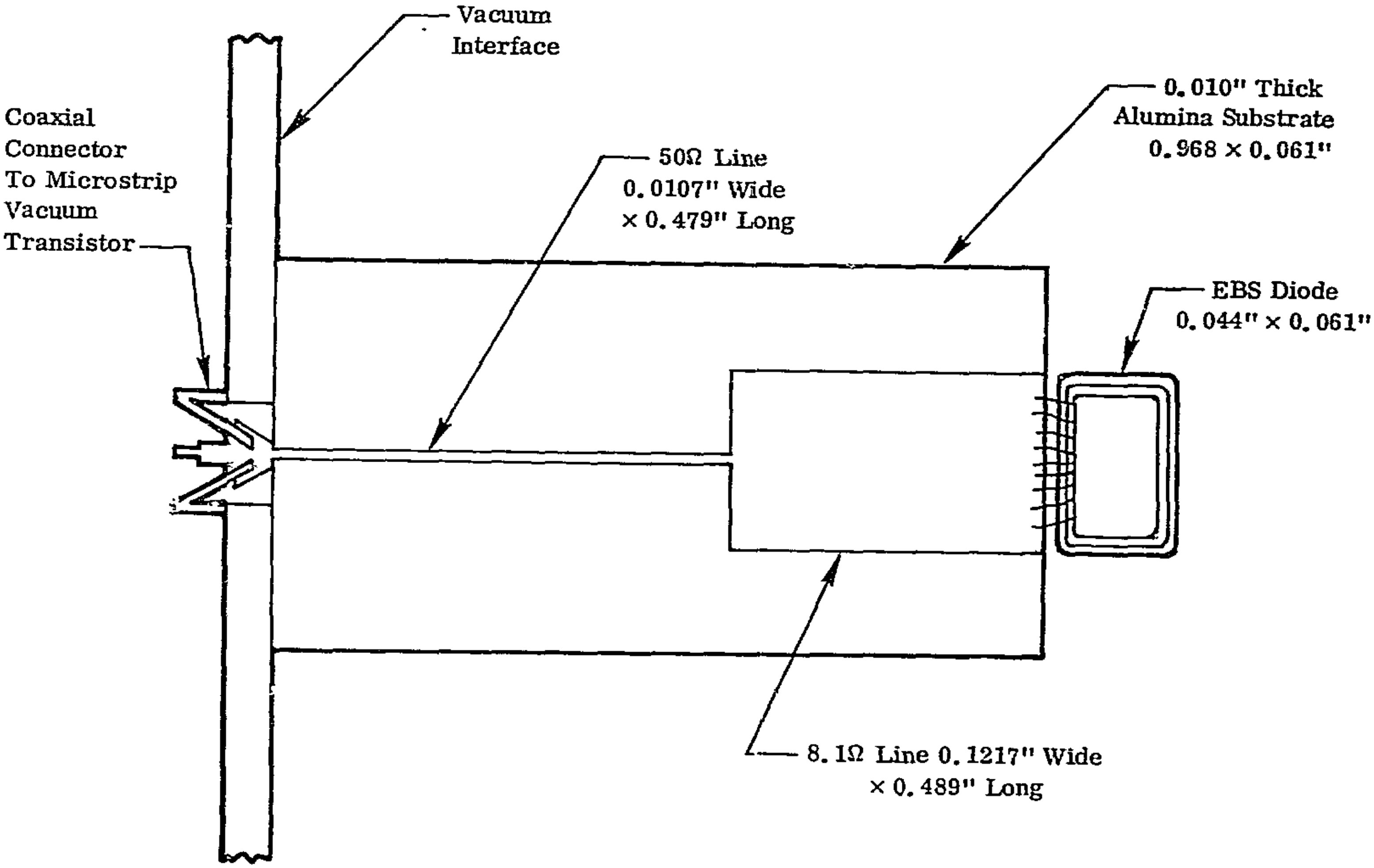

Figure 18 – Microstrip Target Configuration.

Substrate 0.0254 cm Thick ±.00076 cm 99.6% Alumina

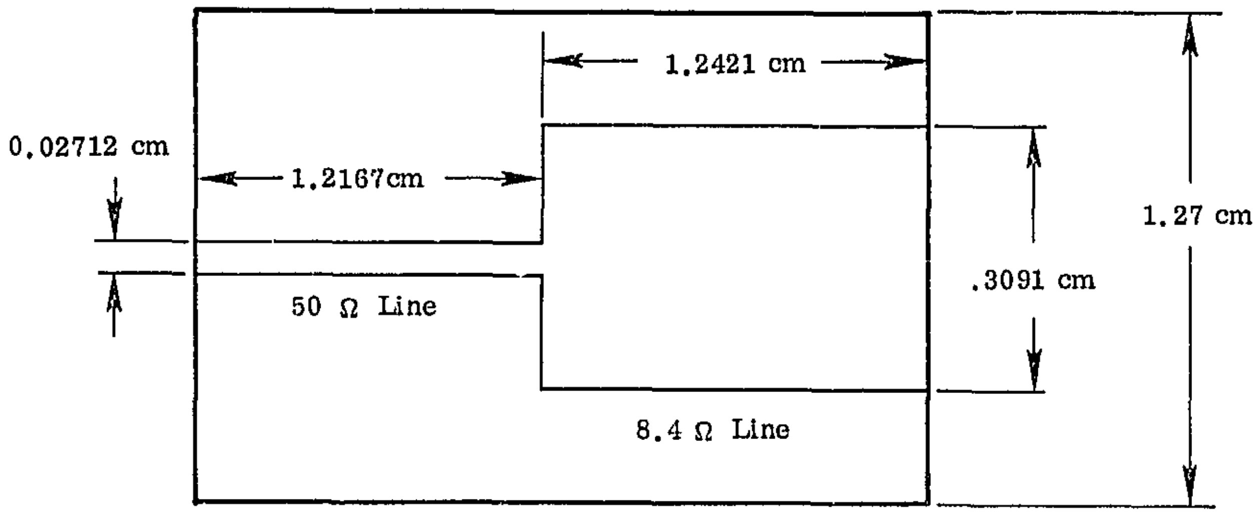

Figure 19. Microstrip Resonator Dimension

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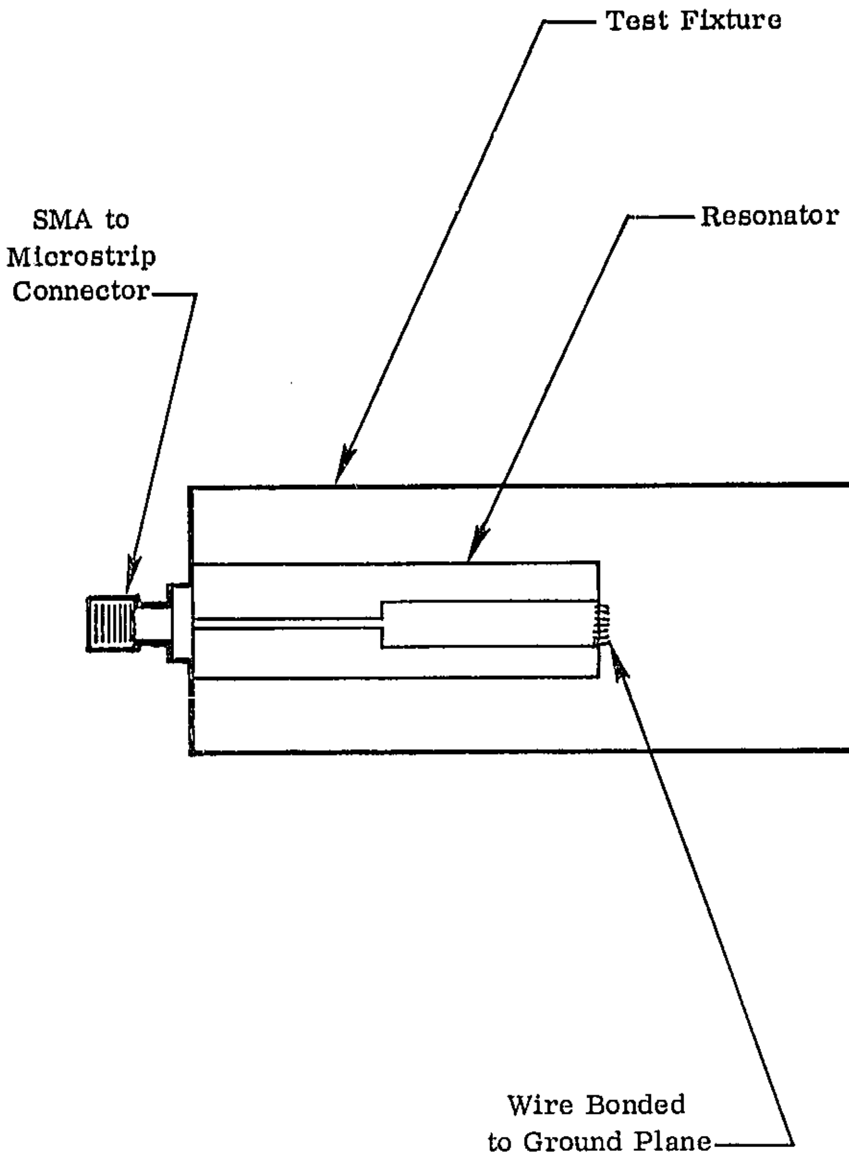
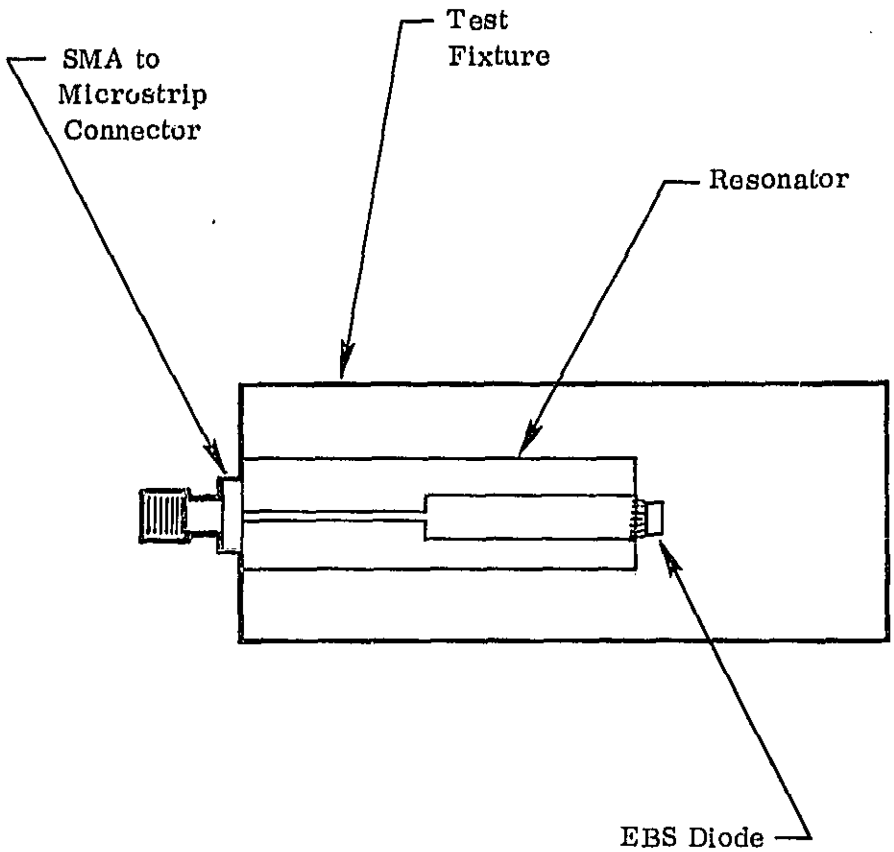


Note: Fixture was covered with a lid spaced the proper height above the ground plane.

Figure 20. Test Resonator Mounted On Test Fixture With Wire Bonds Forming an RF Short



Fixture was covered with a lid spaced the proper height above the ground plane.

Figure 21. Completed Test Microstrip Target

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The unloaded Q for the circuit was also determined as approximately 20. This results ina combined circuit and diode loss of 0.25 ohm. .. expected circuit efficiency using the coupling factor observed should be on the order of 70 percent. This should give an overall target efficiency of near 56 percent.

Several other tasks need to be completed before an amplifier can be built. A transition from microstrip to coaxial line must be designed and tested. Initial design of the transition and the coaxial transmission line is complete. Some test units remain to be built and tested prior to use within an amplifier. Measurements of the coaxial to vacuum interface connector were completed and showed sufficiently low VSWRS 1.2:1 per pair of assemblies (Fig. 22).

VII. VARIABLE COUPLING CAPACITOR MEASUREMENTS

Question has remained for some period of time whether or not the variable capacitor disc used for coupling the RF power from the radial resonator is optimum. Most amplifiers built thus far cannot be overcoupled by a very wide margin. This means that the coupling capacitance is too low. Calculations show that increases in coupling capacitors would provide increased target efficiency with a slightly reduced RF output power.

Currently the coupling capacitor diameter used is 0.220 inches in diameter. A test fixture was assembled which permitted an evaluation of the maximum coupling which could be provided with three different size coupling capacitors; 0.180, .220, and 0.260 inch diameter. Measurements showed a clear improvement in the 0.220 inch diameter over the 0.180 inch diameter disc. The larger disc should reduce coupling over the 0.220 inch disc. In addition the separation between the disc and the ground plane coaxial line was varied to see what effect to coupling might exist. There appeared to be no measurable effect within a spacing range of 0.010 and 0.025 inches.

VIII. MILESTONES AND NEXT QUARTER'S PLAN

Considerable progress has been achieved this quarter towards realizing a major goal. The 10 watt CW performance of a single diode amplifier was another significant step toward the 17 watt goal. It is expected that this goal will be reached during the next period. The old milestone plan is shown in Fig. 23. The new milestone plan is shown in Fig. 24.

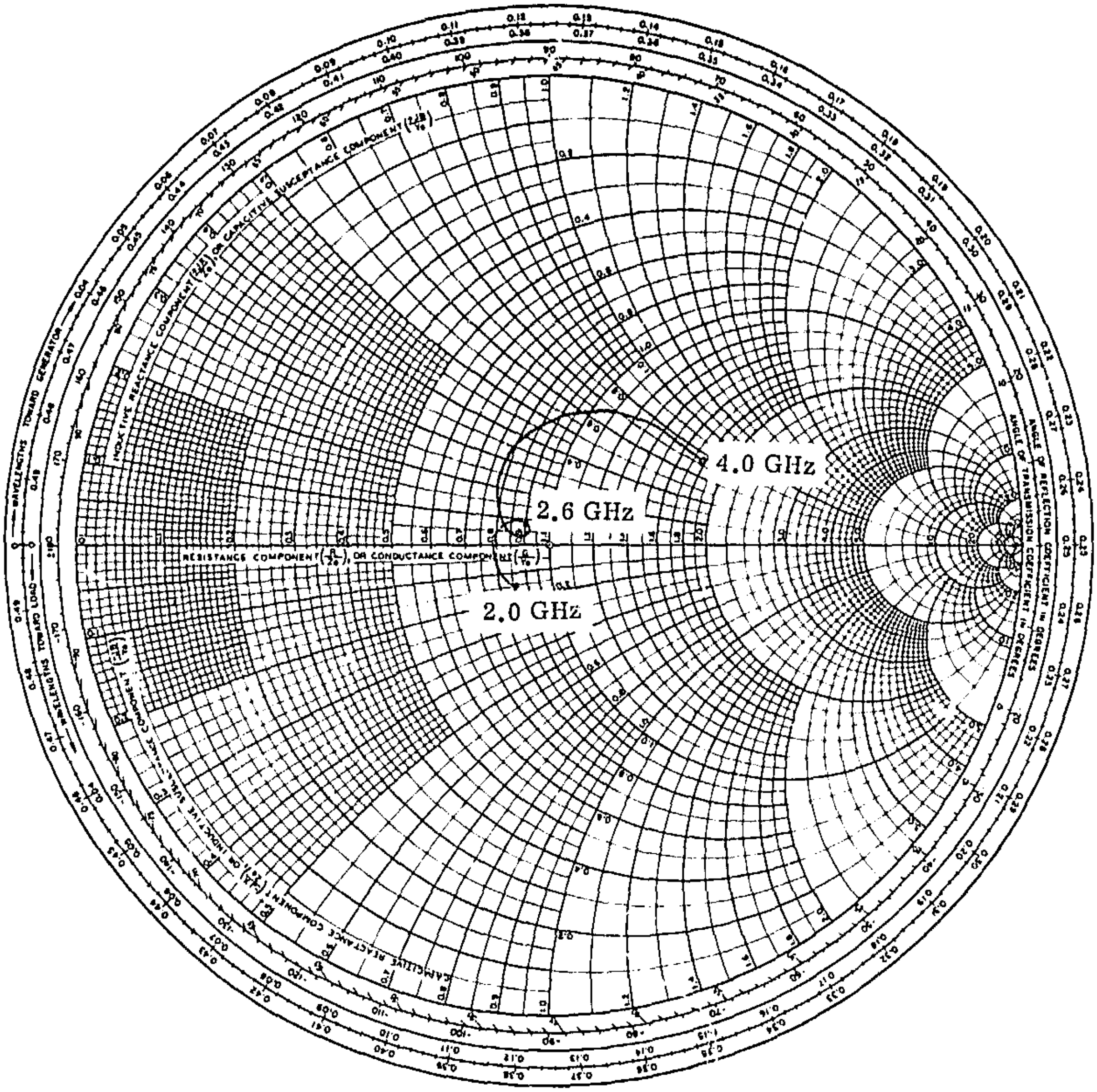

Figure 22 - Impedance of two vacuum connector assemblies with coaxial line between.

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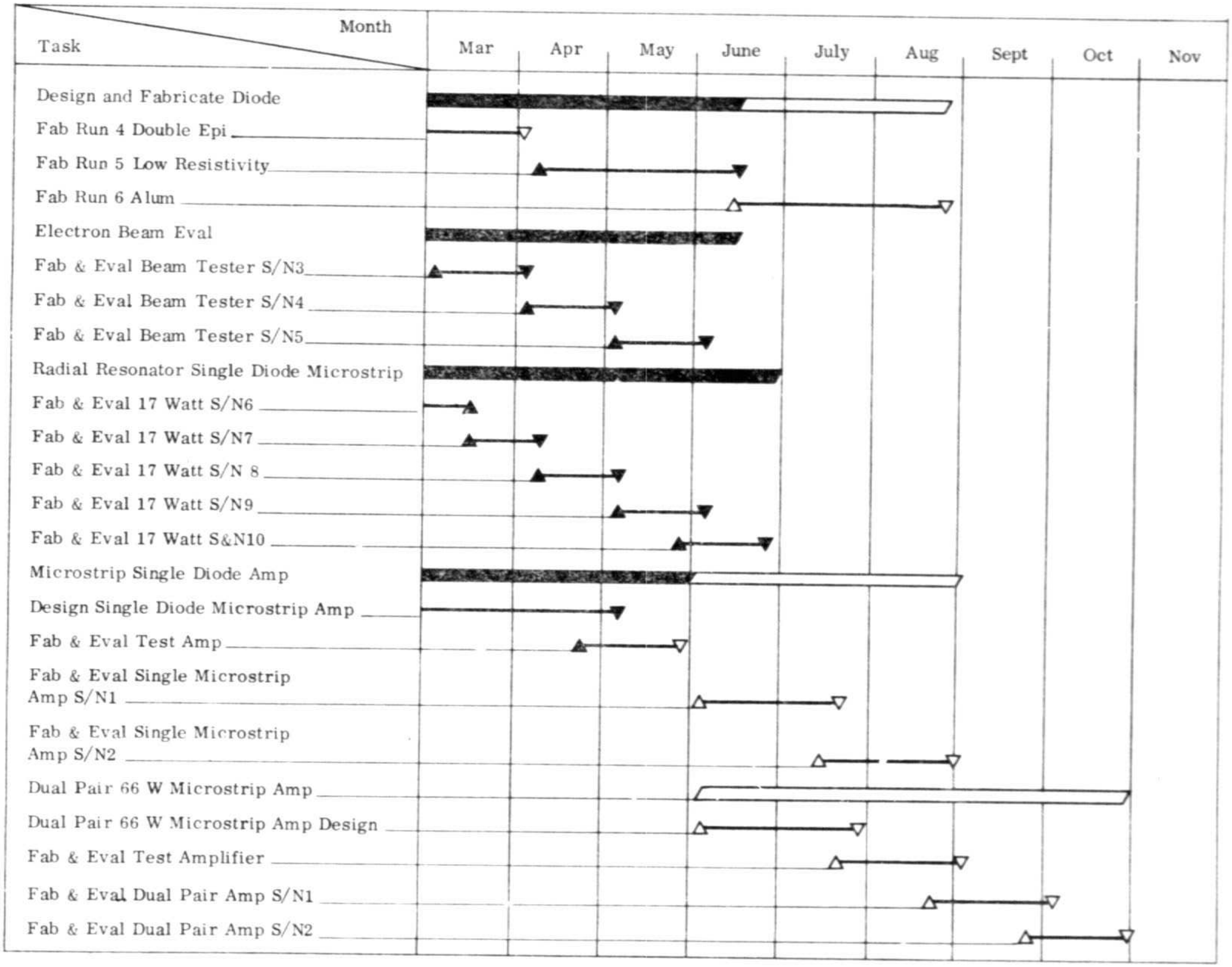

Figure 23 - Old milestone plan.

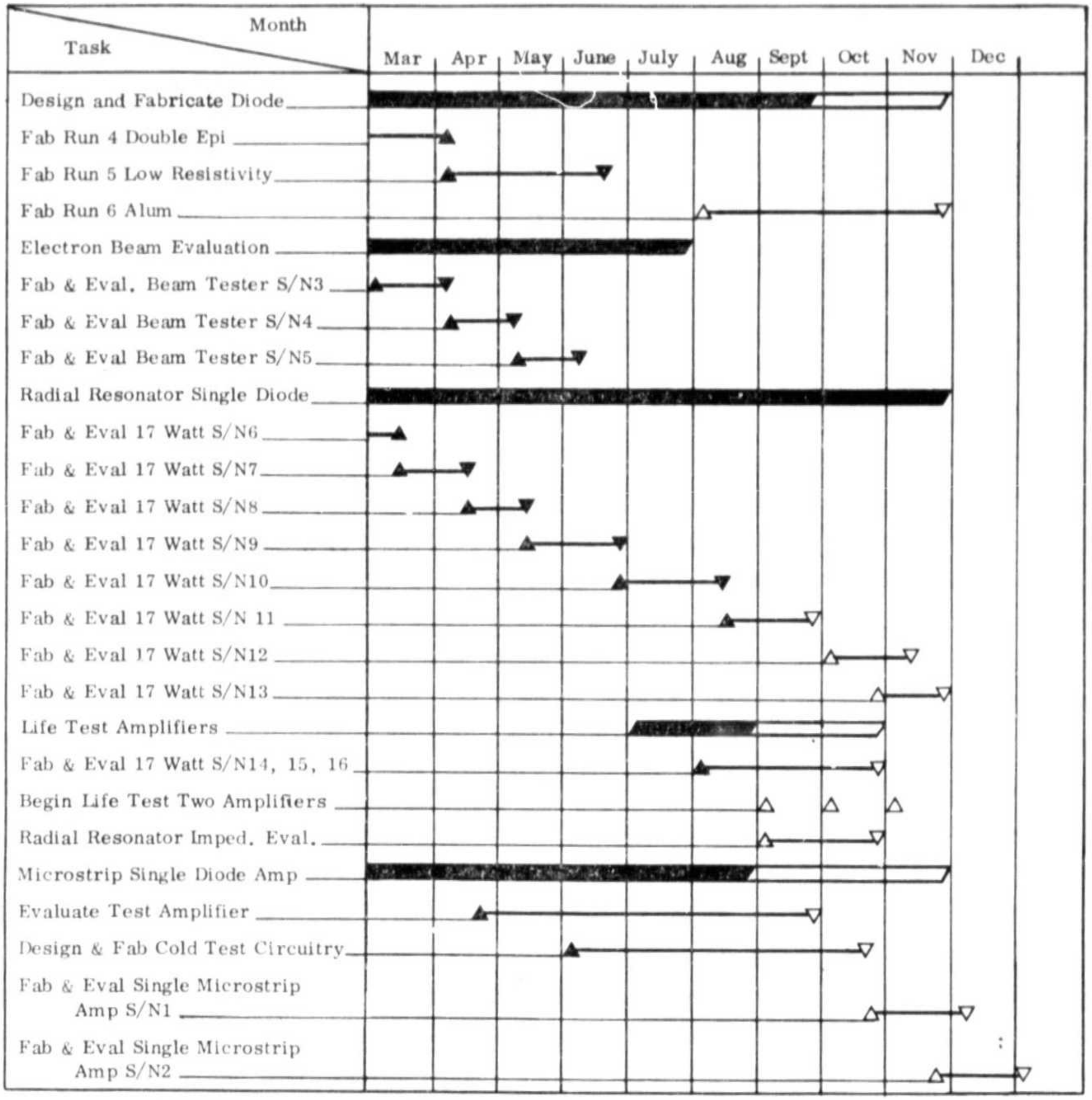

Figure 24 - New Milestone Plan

Other efforts during the quarter were not as dramatic but are accomplishing small tasks which will help reach some major milestones ahead. Several wafers of diodes out of both the double epi run and the low resistivity run were completed and diodes from these wafers evaluated. These wafers were in addition to previously completed wafers. Still remaining to be started is the next aluminum diode run. The material determination is pending the performance on the next few amplifiers. Hopefully material can be ordered for processing to commence in October.

Evaluation of two more CRT beam testers S/N 4 and 5, was completed this period. With these testers complete no further testing during the remainder of this program is planned. The testing thus far has established on a firm basis what our present capabilities are for the size of beam required in S-band EBS deflected beam amplifiers.

Two more single diode radial resonator amplifiers were completed during this quarter. The success achieved with the lower resistivity diode should be extended to the 17 watt level early next period. Additional amplifiers S/N 11 - 13, are expected in order to establish this milestone. S/N 11 is now in progress and should be complete early this quarter. Evaluation of amplifiers using the double epi material will not come until late November. Possibly the other material will be available for evaluation at that time.

An extension to this contract calls for the fabrication and testing of two life test amplifiers. The hardware for these devices has been started with some assemblies now being put together. It is expected that an amplifier will be put on life test early in September. Higher powered units are expected to be placed on life test as they become available.

Some additional impedance evaluation of the radial resonator is now timely and should lead to further target improvements through better understanding of what controls the RF impedance the diode operates at. This work will require fabrication of several test fixtures using the current radial resonator design. In addition, some modification to the current design would be expected, in order to improve impedance characteristics. This would ultimately lead to increased target efficiency with higher output power levels.

The microstrip amplifier development is progressing smoothly but is taking a back-seat to the radial resonator amplifier development. A few more tasks remain to be completed prior to building an actual amplifier. The connector to microstrip interface must be designed and tested. These tasks should be completed in October. At that point little time will be required to get an amplifier built and evaluated.